ICESat Antarctic elevation data: Preliminary precision and accuracy assessment

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[1] Since 'first light' on February 20th, 2003, NASA's Ice, Cloud, and land Elevation Satellite (ICESat) has derived surface elevations from ∼86°N to 86°S latitude. These unique altimetry data have been acquired in a series of observation periods in repeated track patterns using all three Geoscience Laser Altimeter System (GLAS) lasers. Here, we focus on Antarctic ice sheet elevation data that were obtained in 2003–2004. We present preliminary precision and accuracy assessments of selected elevation data, and discuss factors impacting elevation change detection. We show that for low slope and clear sky conditions, the precision of GLA12 Laser 2a, Release 21 data is ∼2.1 cm and the relative accuracy of ICESat elevations is ±14 cm based on crossover differences. **Citation:** Shuman, C. A., H. J. Zwally, B. E. Schutz, A. C. Brenner, J. P. DiMarzio, V. P. Suchdeo, and H. A. Fricker (2006), ICESat Antarctic elevation data: Preliminary precision and accuracy assessment, *Geophys. Res. Lett.*, *33*, L07501, doi:10.1029/2005GL025227.

1. Introduction

[2] The primary objective of ICESat is to provide consistent, repeated surface elevations of Antarctica and Greenland, thereby enabling precise change detection and improved mass balance assessments over the mission lifetime [*Zwally et al.*, 2002]. Technical issues with the lasers have reduced data acquisition from a planned continuous mode to discrete operation periods [*Abshire et al.*, 2005; *Schutz et al.*, 2005]. These problems also caused a reduction in the planned spatial coverage. Despite this, ICESat has provided extensive, detailed ice sheet elevation data with excellent precision and accuracy statistics. Here we illustrate both the quality of the data and suggest some of the challenges to achieving improved data in the future. This paper will focus on Antarctic data to manage its scope but these results generally pertain to Greenland and other large ice masses.

[3] Elevations from the GLA12 Antarctic and Greenland Ice Sheet Data Product from the first three operations periods (Laser 1, Laser 2a, and Laser 2b) are shown in Figure 1. These initial periods had different spatial and temporal characteristics; subsequent operations to date are all spatially similar to the Laser 2b coverage (Figure 1c). The GLA12 elevations were derived using the "standard fit", where each value corresponds to the centroid of a Gaussian fit to a return pulse [*Brenner et al.*, 2003]. During Laser 1, ICESat operated in an 8-day repeat orbit; this provided ∼5 passes along each track during a ∼38 day period (Figure 1a). This track pattern was initially continued for ∼9 days in the Laser 2a period; it was then followed by ∼46 days of a 91-day repeat pattern (Figure 1b). The Laser 2b period and subsequent periods have repeated the last ∼33 days of the Laser 2a observations [see *Schutz et al.*, 2005, Table 1]. Laser 2a's greater spatial coverage is clearly seen in Figure 1b; specific geographic references used in this paper are shown in Figure 1a.

[4] Close examination of these track maps shows the effects of clouds that can cause irregular gaps in the elevation profiles. This effect is most severe over the ocean but also has a significant impact on parts of West Antarctica (Figure 1c [see *Spinhirne et al.*, 2005]). Despite clouds, the amount of altimetry data acquired by ICESat is large; GLAS emits >350,000 shots over Antarctica each operational day and receives a surface return from >80% of the pulses; this value can vary from ∼77 to 86%. By comparison of repeat tracks and 'crossovers', ICESat data can enable ice sheet change detection [e.g., *Smith et al.*, 2005].

2. ICESat Precision and Relative Accuracy

[5] We examine the ICESat data in two ways. First, we use repeat track data from Laser 2a (Release 21) and Laser 3a (Release 23) to illustrate precision and to show some of the challenges of using the data for elevation change detection. Second, we perform a crossover analysis of Laser 2a elevations to assess their 'relative accuracy'. Crossover residuals provide a relative measure of accuracy since the elevations are being compared to themselves, not to an independently defined reference surface [e.g., *Fricker et al.*, 2005].

2.1. Precision and Repeat Track Analyses

[6] This repeat-track analysis illustrates both ICESat's precision and its ability to closely remeasure a specific topographic profile. We chose data across Lake Vostok in East Antarctica (see Figure 1a) because of this area's low slope and accumulation [*Studinger et al.*, 2003]. ICESat Track 0071 crosses ∼235 km of this feature and was

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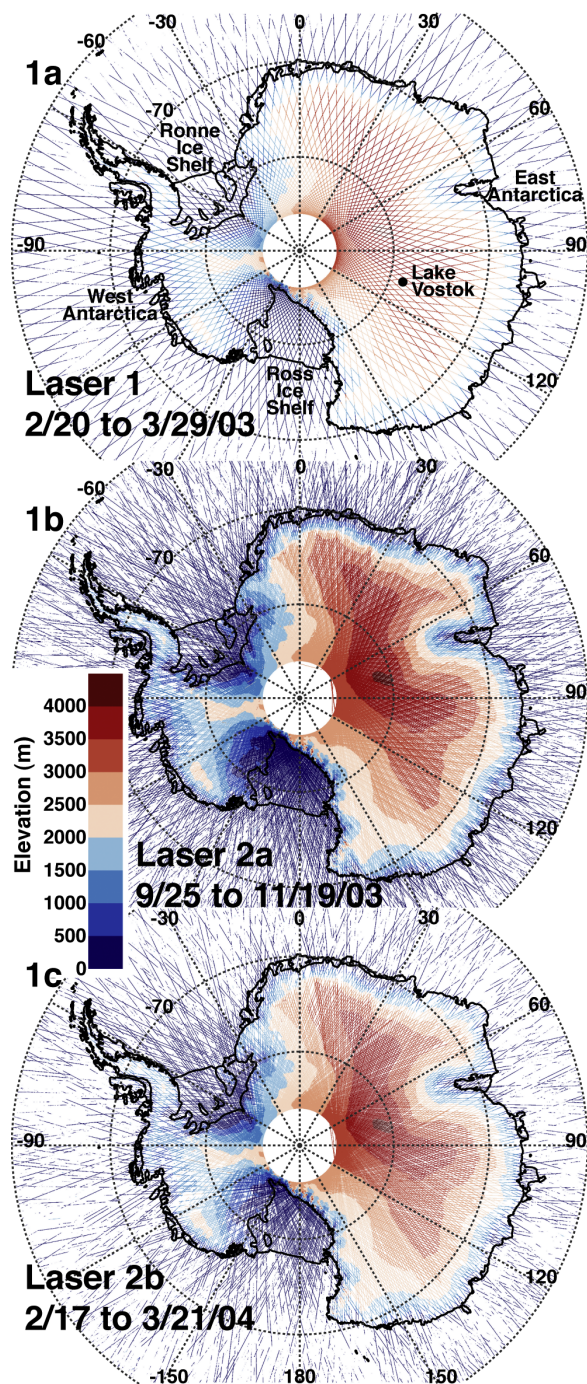
Figure 1. Coverage maps of ICESat's Laser (a) 1, (b) 2a, and (c) 2b operation periods over Antarctica. Irregular gaps in the coverage indicate the presence of clouds that prevented elevation determination.

acquired on 10/26/03 (Laser 2a) and on 10/14/04 (Laser 3a). The surface's gentle slope is shown in Figure 2a; the elevation rises only ~30 m across the area. Ancillary data indicate that both profiles were obtained through clear skies so the potential atmospheric impact is small. However, GLAS detector saturation affects these data [*Abshire et al.*, 2005] and this leads to elevations that are 10s of cm too low. Correction is currently possible over low slopes [*Sun et al.*, 2004; *Fricker et al.*, 2005] and the average correction for the

Laser 2a profile was ~32 cm with a standard deviation (SD) of ~4.9 cm. The corresponding values for the Laser 3a data were ~27 and 5.7 cm, respectively.

[7] We estimate ICESat's precision for both repeats by calculating the shot-to-shot variability in the saturation-corrected GLA12 elevation profiles relative to a 9-point (~1.5 km) running mean. We then differenced the original from the mean elevation profile (Figure 2a). The difference values are usually below 5 cm for both profiles and the ~1100 individual differences show a SD of ~2.1 and ~2.3 cm for Laser 2a and Laser 3a, respectively. This shot-to-shot precision exceeds the expected value of 10 cm per pulse for ice sheet interiors [*Zwally et al.*, 2002].

[8] In order to evaluate any elevation change over the ~1 year period, we compared the Laser 2a and 3a repeats of Track 0071 (Figure 2b). We determined the horizontal and vertical separation between the two profiles by aligning them to minimize the distance between the individual measurement points, and then calculated each separation. Because of orbital variations, the tracks are not parallel and the cross-track distance varies from ~25 m to ~85 m in this case. Also note the ~1 Hz oscillation of the cross-track distance between the two profiles as discussed by *Schutz et al.* [2005]. The Laser 2a elevations are generally higher than those from Laser 3a, and this difference varies over ~35 cm range (Figure 2b). Since the tracks do not repeat exactly, a small part of these differences is from cross-track slope. Using a cross-track slope derived from other ICESat data, this factor contributes up to 1.5 cm, which is much smaller than the derived elevation difference signal. It is unlikely that the magnitude of the surface elevation change at Vostok over one year is as high as these results suggest, nor that any real change has this spatial variability. We conclude that the ICESat data currently contain small but perceptible geo-location and other possible errors and therefore cannot yet be used to determine elevation changes at this level. See further discussion given by *Luthcke et al.* [2005] and in the text below.

2.2. Crossover Analysis

[9] We define a crossover residual as the difference in elevation between two altimetry profiles that intersect [*Zwally and Brenner*, 2001]. Once the intersection point (or crossover location) for the pair of profiles is calculated, the elevations at the crossover are calculated by linearly interpolating from the two observed elevations on each side of the intersection point for each pass. The crossover residual is the difference in the interpolated elevations from the two passes. If valid elevations do not exist on both sides of the crossover location (ICESat elevations are every ~172 m along track), then that crossover is discarded. We note that the interpolation distance is similar to or greater than the cross track distances for the repeat track analysis above. We calculated the statistics (mean and SD) for a set of crossovers after using a 3 SD iterative edit to remove outliers. The largest residuals are due to 'elevations' that are occasionally derived from cloud tops. We defined the slope for each crossover based on its location on the NASA/GSFC 5 km Antarctic DEM created from GEOSAT and ERS-1 geodetic radar data [*Zwally and Brenner*, 2001] and calculated the crossover statistics for specific slope classes (see Table 1).
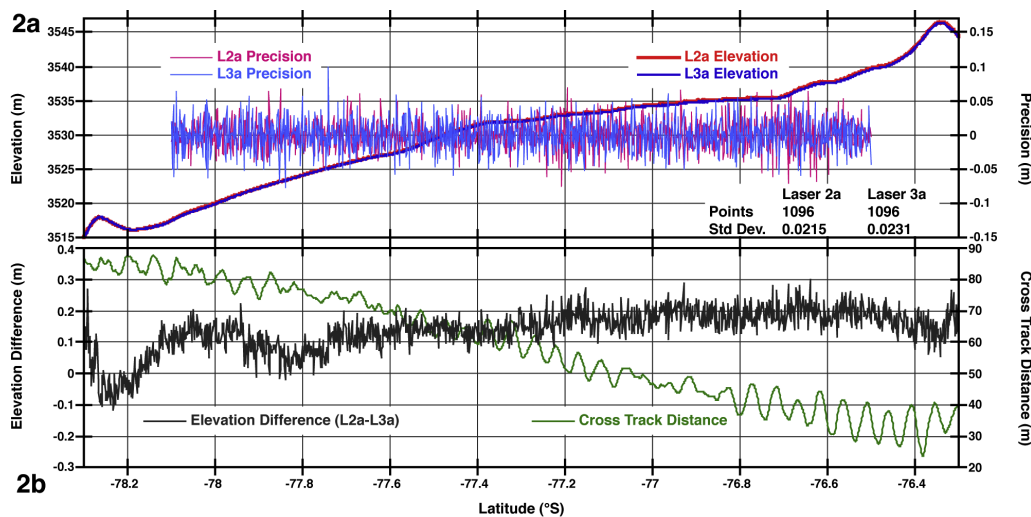
Figure 2. Comparison of ICESat GLA12 data for Track 0071 across Lake Vostok for Laser 2a (Release 21) and Laser 3a (Release 23). (a) The vertically exaggerated (~1800x) GLA12 elevations (left y-axis) have been corrected for saturation. The precision data from the two profiles are plotted (right y-axis) and summarized statistically. (b) The resulting elevation differences (left y-axis) and cross-track separation (right y-axis) between the repeat tracks are discussed further in the text.

[10] Figure 3 shows the locations of the crossovers derived from all the Laser 2a data. We did not perform a saturation correction since it cannot yet be applied to all slopes. The scale bar covers a range of ±1.1 m to accommodate the approximate crossover residual range that results from the iterative editing. About 3% of all the residuals have values outside this range, and are associated with steeply sloping areas, the largest tidal variations of ice shelves, and elevations from clouds that were misinterpreted as 'ground'. A discrete area of large crossover differences over the Ross Ice Shelf (RIS) is clearly seen in Figure 3. As discussed by *Padman and Fricker* [2005], the ocean tide model applied to ICESat data is not optimal for ice shelves. To avoid emphasizing the tide model's impact, these corrections were removed before further analyzing the crossovers. Especially over the RIS, the resulting residuals reflect the ice shelf tidal stage between ICESat passes. The clear distinction between grounded (small crossover values) and floating (large crossover values) areas suggests that ICESat data can help determine the location of ice shelf grounding lines.

[11] About 51% of the crossover residuals plotted here are within the +0.1 to −0.1 m (gray) increment. Figure 3 also demonstrates the increase in crossover frequency with latitude to a maximum where all tracks converge near 86°S. Elevation data gaps in a single track due to cloudy conditions (see Figure 1) also cause 'missing' crossovers (e.g., on the Ronne Ice Shelf). Additional near-linear data gaps in the overall crossover pattern are due to the exclusion of Round-The-World (RTW) and Target Of Opportunity (TOO) tracks that are acquired with spacecraft off-nadir pointing [*Schutz et al.*, 2005; *Luthcke et al.*, 2005]. Off-nadir pointing can cause fairly large elevation differences due to the 'artificial slope' that is induced. To assess ICESat's relative accuracy with the most consistent data, all off-nadir and all ice shelf crossovers (or ~27% of all Laser 2a crossovers), were removed from the following statistics.

2.3. Crossover Statistics

[12] The crossover data for all of Antarctica, except as noted above, are summarized in Table 1, line 1. The mean

for all crossovers residuals derived from the Laser 2a period is close to zero; the SD, a simple measure of ICESat's overall relative accuracy, is 14.4 cm. However, this value is derived from data across most of Antarctica and thus includes crossovers from some steep slopes. To evaluate the impact of slope, we grouped the crossover data into slope classes based on the NASA/GSFC 5 km Antarctic DEM (Table 1). The first slope class, 0 to 0.25°, has the best relative accuracy (13.85 cm) and comprises the majority of the observations. Note that the Vostok repeat track ~1 year elevation differences are largely within this plus/minus range. This suggests that the uncertainty in the repeat track 'change' values is consistent with the uncertainty in overall ICESat accuracy. The steepest slope classes (>1.25°) have the fewest observations and the largest SD values (>25 cm). The means for all the slope classes are within 2 cm of zero and vary in sign; this variability does not have a clear explanation considering the magnitude of the associated SD values but may be related to real processes such as accumulation. For example, as the Laser 2a period was ~55 days long, the time-span between tracks for a given crossover residual may reflect real snow and ice elevation changes [e.g., *Bindschadler et al.*, 2005].

Table 1. Laser 2a Release 21 Ascending-Descending Crossover Statistics[a]

Area	Points (3SD)	Mean, cm	SD, cm
Antarctica	160740	−0.097	14.437
0 to 0.25°	127538	−0.173	13.854
0.25 to 0.5°	19731	0.288	16.457
0.5 to 0.75°	7038	0.141	19.566
0.75 to 1.0°	3363	−0.986	21.321
1.0 to 1.25°	1988	−1.969	23.879
1.25 to 1.5°	1228	−0.294	26.541
1.5 to 2.0°	867	−1.818	25.255

[a]Crossovers from ice shelves and off-nadir profiles were removed from these statistics.
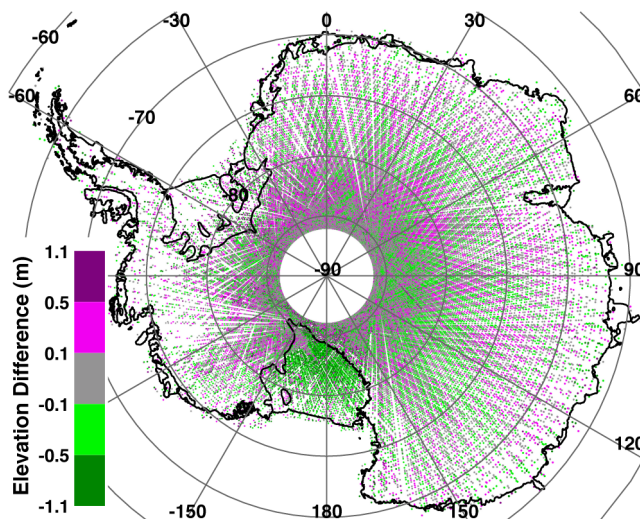
Figure 3. Map of Laser 2a crossover residuals over Antarctica. The tide correction in the standard processing algorithm has been removed to reveal true ice shelf elevation variability. The crossovers are plotted in decreasing absolute magnitude order.

3. Factors Impacting Change Detection

[13] The repeat track and crossover results presented here indicate that ICESat Laser 2a GLA12 elevation data have a relative accuracy of about ±14 cm and a precision of just over 2 cm. Remaining uncertainties in ICESat pointing knowledge [*Schutz et al.*, 2005] may still impact elevation data, especially time-varying differences within and between operational periods [*Luthcke et al.*, 2005]. Saturation correction is necessary for Laser 2a and Laser 3a as well as portions of other operation periods [*Abshire et al.*, 2005; *Fricker et al.*, 2005] and this correction can be substantial (~30 cm). Cloud-cover varies in time and space and can subtly influence the accuracy of the elevation data or even prevent their acquisition [*Spinhirne et al.*, 2005; *Fricker et al.*, 2005]. No cloud filtering was applied in this study and filtering techniques [e.g., *Smith et al.*, 2005] are still being developed. Extrapolation of elevations from repeated or intersecting tracks 10s to 100s of meters across real, local topography is also a factor in determining elevation change through time. Thus, using ICESat data for ice sheet elevation change and mass-balance studies requires awareness and/or correction of these issues before changes at the decimeter-level can be confidently derived.

4. Summary

[14] This paper introduces the ICESat elevation data for Antarctica and quantifies its current precision and relative accuracy. Based on the Laser 2a period, these results document ICESat's ability to assess the Antarctic ice sheet's surface elevations and suggest the magnitude of its minimum change detection ability. In the near future, each operations period through the mission lifetime will be similarly characterized. Discerning elevation change with time is clearly possible but some limitations inherent to the data must be considered especially if the signal is at the few decimeter level or below. Given the excellent precision and accuracy possible from ICESat, for most glaciological studies the main limitation for studying specific areas may be availability of data due to reduced spatial or temporal coverage, and/or cloud cover. ICESat data are currently enabling definition of ice sheet topography with a resolution not available from other existing satellite instruments.

References

Abshire, J. B., X. Sun, H. Riris, J. M. Sirota, J. F. McGarry, S. Palm, D. Yi, and P. Liiva (2005), Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance, *Geophys. Res. Lett.*, *32*, L21S02, doi:10.1029/2005GL024028.

Bindschadler, R., H. Choi, C. Shuman, and T. Markus (2005), Detecting and measuring new snow accumulation on ice sheets by satellite remote sensing, *Remote Sens. Environ.*, *98*, 388–402.

Brenner, A., et al. (2003), Derivation of range and range distributions from laser pulse waveform analysis for surface elevations, roughness, slope, and vegetation heights, Algorithm Theoretical Basis Document, version 4.1, Cent. for Space Res., Univ. of Tex., Austin. (Available at http://www.csr.utexas.edu/glas/atbd.html)

Fricker, H. A., A. Borsa, B. Minster, C. Carabajal, K. Quinn, and B. Bills (2005), Assessment of ICESat performance at salar de Uyuni, Bolivia, *Geophys. Res. Lett.*, *32*, L21S06, doi:10.1029/2005GL023423.

Luthcke, S., D. Rowlands, T. Williams, and M. Sirota (2005), Calibration and reduction of ICESat geolocation errors and the impact on ice sheet elevation change detection, *Geophys. Res. Lett.*, *32*, L21S05, doi:10.1029/2005GL023689.

Padman, L., and H. Fricker (2005), Tides on the Ross Ice Shelf observed with ICESat, *Geophys. Res. Lett.*, *32*, L14503, doi:10.1029/2005GL023214.

Schutz, B. E., H. J. Zwally, C. A. Shuman, D. Hancock, and J. P. DiMarzio (2005), Overview of the ICESat Mission, *Geophys. Res. Lett.*, *32*, L21S01, doi:10.1029/2005GL024009.

Smith, B., C. Bentley, and C. Raymond (2005), Recent elevation changes on the ice streams and ridges of the Ross Embayment from ICESat crossovers, *Geophys. Res. Lett.*, *32*, L21S09, doi:10.1029/2005GL024365.

Spinhirne, J. D., S. P. Palm, and W. D. Hart (2005), Antarctica cloud cover for October 2003 from GLAS satellite lidar profiling, *Geophys. Res. Lett.*, *32*, L22S05, doi:10.1029/2005GL023782.

Studinger, M., et al. (2003), Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica, *Earth Planet. Sci. Lett.*, *205*, 195–210.

Sun, X., J. B. Abshire, and D. Yi (2004), Geoscience Laser Altimeter System: Characteristics and performance of the altimeter receiver, *Eos Trans. AGU*, *84*(46), Fall Meet. Suppl., Abstract C32A-0432.

Zwally, J., and A. Brenner (2001), Ice sheet dynamics and mass balance, in *Satellite Altimetry and Earth Sciences*, edited by L. Fu and A. Cazenave, pp. 351–369, Elsevier, New York.

Zwally, J., et al. (2002), ICESat's laser measurements of polar ice, atmosphere, ocean and land, *J. Geodyn.*, *34*, 405–445.

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